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Vol. 6

September-October, 1950

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ATOMICS

ANDREW W. KRAMER, *Editor*

Nothing to Worry About . . . Usually, in these uncertain days, we spend most of our time contemplating the horrors of atomic, biologic and misguided missile warfare and, to be honest, it gets us down. Every day the literature becomes more forboding. With atomic powered flying disks from Moscow and Venus zooming around the planet, communists under every desk in the State Department, radioactive sand raining down on the Pentagon, Broadway and Hollywood, the struggle to go on, often seems hopeless and we find ourselves on the point of stepping off the window ledge into space. But always, at this psychological instant, a piece blows our way, or there is a radio announcement, which makes us reconsider, and we put off the fatal moment. Listen, for example, to the item we noticed today, just as we were getting ready to open the window. It was an announcement in the Chicago American concerning "Chicago defense officials plans" to cope with an atomic bomb attack here, when it comes. And, as they say over the radio—we quote, "Chicago defense officials today pin pointed A and B targets for the make-believe enemy A-bomb attack here between September 25 and 29. Maps in Fire Marshal Anthony Mullaney's civil defense headquarters indicate the A target of the imaginary bomb will be the steel mill area in South Chicago."



ATOMICS

is published bi-monthly by

TECHNICAL PUBLISHING CO.

110 South Dearborn Street
CHICAGO 3, ILLINOIS

KINGSLEY L. RICE.....*President*
EDWIN C. PROUTY.....*Exec. Vice Pres.*
WALTER PAINTER.....*Vice President*
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SUBSCRIPTION INFORMATION:

United States and Possessions, one year \$5.00, Canada, one year \$5.50, Other countries, one year \$6.00. Single copies, U.S.A. \$1.00, other countries, \$1.25.

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So far, this sounds rather reasonable, in fact we sort of had the same idea ourselves but, of course, having no official status in the A-bomb defense system, we shrugged off the thought as a mere mental aberration. However, the next sentence of the article was more astonishing. Quoting again, "The B target will be at Halsted and 16th Streets."

This was both startling and reassuring. Perhaps some of you are not familiar with Chicago. Well, for you, it will be enough to know that Halsted and 16th Streets is not what one would commonly regard as a nice neighborhood, from any standpoint. It is somewhat submarginal, rather crummy in fact. Sure, there are a couple of Mexican hash houses around there but when we read that it was to be the B target, it seemed like a good place for Uncle Joe to waste an A-bomb if he was so disposed.

However, it is unwise to jump at conclusions in any case, and it was in this instance because we had com-

pletely discounted the astute thinking of Fire Marshal Mullaney and his staff of pyrotechnicians.

Why Halsted and 16th streets? Well, read it for yourselves. Quoting again. "The Loop district was counted out as a blast area, it was said, because it would be assumed that the 'enemy miscalculated its aim and the bomb fell short of the intended target.' "

Gosh all hemlock, who would have thunk it? It seemed astonishing that mere human brains could have been capable of such "pin pointing" without the aid of ENIAC or at least an analog computer but investigation on our part disclosed the fact that our civil defense headquarters has no such gadget. "Waddyamean do we have a nanna logcomputer? This is the fire department, see," said the voice over the phone. We saw.

So, for the time being we can face the future with a degree of reassurance. Halsted and 16th streets is about a mile and a half from where we are pounding this typewriter and if Uncle Joe is going to make this miscalculation we don't have to worry about a thing.

We feel a little selfish about it, however. We know that other places can not be as fortunate as we are in having such astute minds in charge of their A-bomb defenses and it seems unfair that the mental brilliance of our Chicago Defense officials cannot be made available to the nation as a whole. It seems to us, though, that we read somewhere that there was no defense against the A-bomb, but maybe we just imagined that.

Oh yes, there is more, and once more, we quote: "A map adjoining the 'target' indicator in Mullaney's HQ, graphically pictured what will happen after two simulated simultaneous blasts. Planning preventive measures are Battalion Chief Edward Newell and Chief Frank McAuliffe. Firemen and equipment from all of Cook County and seven adjacent counties will race to the two "disaster" points to quench the ensuing conflagration. The combined fire-fighting forces will ring the flaming areas, connecting with every available water source to stop the spread of fire, including the lake, park pools, the river, lagoons and operating hydrants." Boy! Ain't that somethin'?

Well, it is highly reassuring to know that everything is under control and for a while at least we are going to keep away from the window ledge—life looks pretty good again. But—well, maybe we shouldn't mention it, it is probably just a passing thought—another mental aberration—but suppose Uncle Joe decides to fly over the North Pole as some people say he is going too, then, what will happen? Then, coming from the North, if he miscalculates, the B target will be around Chicago Avenue—near the Palmolive Building.

Oh well, suppose he does, we still don't have to worry. Chicago Avenue is also over a mile from here.



Radioactivity Induced in Water

This article presents the basic information and formulae concerning induced radioactivity in nuclear coolants and structural materials. The data should be of considerable worth to physicists, chemical, mechanical, sanitation, nuclear and other engineers

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NUMEROUS articles have been published in the last few years which have discussed qualitatively the formation of radioactive particles in gaseous and water solutions and which have speculated on the public health consequences of radioactivity in water in regard to so-called "atomic plants" and "reactor sites." This article endeavors to present quantitative examples of artificially induced radioactivity, how it is formed in water, how long it exists and how the intensity of radiation varies with time. The basic equations for induced activities on recycling reactor cooling fluids are developed and their use is explained. The quantitative background data and formulations for these evaluations are available in published books¹ and declassified documents². This article is written in order to provide a real comprehension on the part of non-nuclear engineers into the problems and nature of radioactivity induced in reactor cooling waters.

NATURE OF RADIOACTIVITY

Waters containing dissolved radioactive chemical elements have been known since about 1895. Natural radioactive substances are all about us in our environments of land, air and water as well as in our body organs. Naturally occurring radioactive waters have dissolved in them, or carry, radioactive decaying substances such as members of the radium family. These natural concentrations of radioactivity are usually small, but they constitute an intensity level well above that which instruments can easily detect and measure accurately. See Table I. The rapid developments in the various fields of atomic energy and nuclear fission during recent years have created problems which have required solutions and have enlarged the subject considerably. Waters containing artificially induced radioactivities may carry all sorts of water soluble and suspend radioactive decaying chemical elements. The atoms of a radioactive element or isotope are continually decaying from an active to a stable atomic state or element. They give off alpha, beta and gamma particles; and less frequently neutrons. In

water the distance that alpha particles travel is about 10^{-2} mm. Beta particles can travel larger distances, averaging about 10 mm depending on their energies. Gamma rays are similar to X-rays having a short wave length, high energy content and great penetrability through any mass. They can travel several feet in water, hence, at some distances from a water containing radioactive components, the effective radiation is due to gamma particles entirely.

RADIOACTIVE DECAY

All known radioisotopes decay according to a well established quantitative law and no mechanism is known which can change it. The *rate of decay* is directly proportional to N , the number of radioactive atoms present at any time, t ,

$$D = \frac{dN}{dt} = -\lambda N$$

The constant, λ , may be evaluated by determining the time required for one half of the atoms of the isotope under consideration to decay. This half life is written at $t_{1/2}$, and is called the half life of the active isotope. Then, integrating

$$\int \frac{dN}{N} = \int -\lambda dt$$

$$N = N_0 e^{-\lambda t}$$

Where N is the number of active atoms at any time, t , and N_0 is the number of atoms originally present. By proper substitution, the value of λ in

TABLE I

SCALE OF CONCENTRATIONS OF RADIOACTIVITY IN NATURAL AND INDUSTRIAL WATERS (in curies per liter)

10 ⁻¹⁵	One of the lowest recorded natural water backgrounds.
10 ⁻¹⁴	Natural air background over large bodies of water.
10 ⁻¹³	Natural air background over land.
10 ⁻¹²	Pure spring and river waters.
10 ⁻¹¹	Natural background of Pacific and Atlantic Oceans ¹⁰ , Gulf Stream and Earth's crust (100 curies per cubic mile).
10 ⁻¹⁰	Natural background of some tap waters.
10 ⁻⁹	Granite rocks and mineral deposits.
10 ⁻⁸	Old Cave Springs, Glenwood Springs, Colorado ⁹ .
10 ⁻⁷	Magnesium Springs, Hot Springs, Virginia ⁹ .
10 ⁻⁶	Highest known natural water activity near pitchblende mines of Joachimstal, Czechoslovakia.
10 ⁻⁵	"Warm Wastes" ^{**} to ground cribs and retention basins.
10 ⁻⁴	Uranium ores containing radium.
10 ⁻³	"Hot Wastes." ^{**}
10 ⁻²	-----
10 ⁻¹	"Warm" ^{**} laboratory work.
1	-----
10	"Hot" ^{**} laboratory work.

* Arbitrary values.

This tabulated scale of radioactivity concentrations must be evaluated in the light of chemical origins, quantities, radiation intensities, half-lives of active constituents, ingestion, inhalation and immersion tolerances as well as animal organ selective localizations, bodily rates of elimination, and numerous other factors before one can tell if the radioactivity under investigation is of any harmful significance.

terms of $t_{1/2}$ is found to be

$$\lambda = \frac{0.693}{t_{1/2}}$$

The half life of different elements varies from seconds to millions of years; it must be determined experimentally and is a fundamental property of each radioisotope. Obviously, the intensity of radiation is greatly affected by the half life since it appears in the exponential term.

FORMATION OF INDUCED RADIOACTIVITY

Radioactivity is induced in atoms of elements present in water either in solution or in suspension by neutron capture during the time the water is present in a nuclear reactor. For example, in the water-cooled reactors at Hanford, neutron bombardment occurs while the cooling water passes through the reactor. The calculation of the quantity of activity induced in each atomic species is simple. As soon as active atoms form, decay initiates and is a statistical phenomenon. Depending upon the time of neutron irradiation and the half life of the new radioisotope atoms, decay may or may not be important during the time the atom remains in the neutron field. After leaving the reactor, no further production of radioisotopes results, but decay of those formed will continue according to the law developed above.

It is apparent that the method of cooling a reactor by water can be varied in several ways. The water can be used once or it can be recycled many times with or without a purge. Each case is considered in the following sections.

The amount of activity induced in the water depends rather simply on

1) the number of incident neutrons in the flux, nv , where n = density of neutrons per cm^3 and v is their average velocity over the neutron energy spectrum is cm/sec ; neutron energies at room temperature are spoken of as thermal (0.025 eV); energies between thermal and fast are called epithermal; and fast neutrons have very high energies of millions of electron volts.

2) the concentration of target element in atoms per cm^3 is evaluated from A , Avagadro's Number, 6.06×10^{23} molecules per gram atom, W , the atomic weight and C , the concentration fraction of element.

3) the neutron activation or absorption cross section, σ of the element under bombardment expressed in cm^2 or barns, 10^{-24} cm^2 .

As a result, the rate of production of induced activity is expressed by

$$P = \frac{dN}{dt} = (nv) (N_v) (\sigma)$$

where

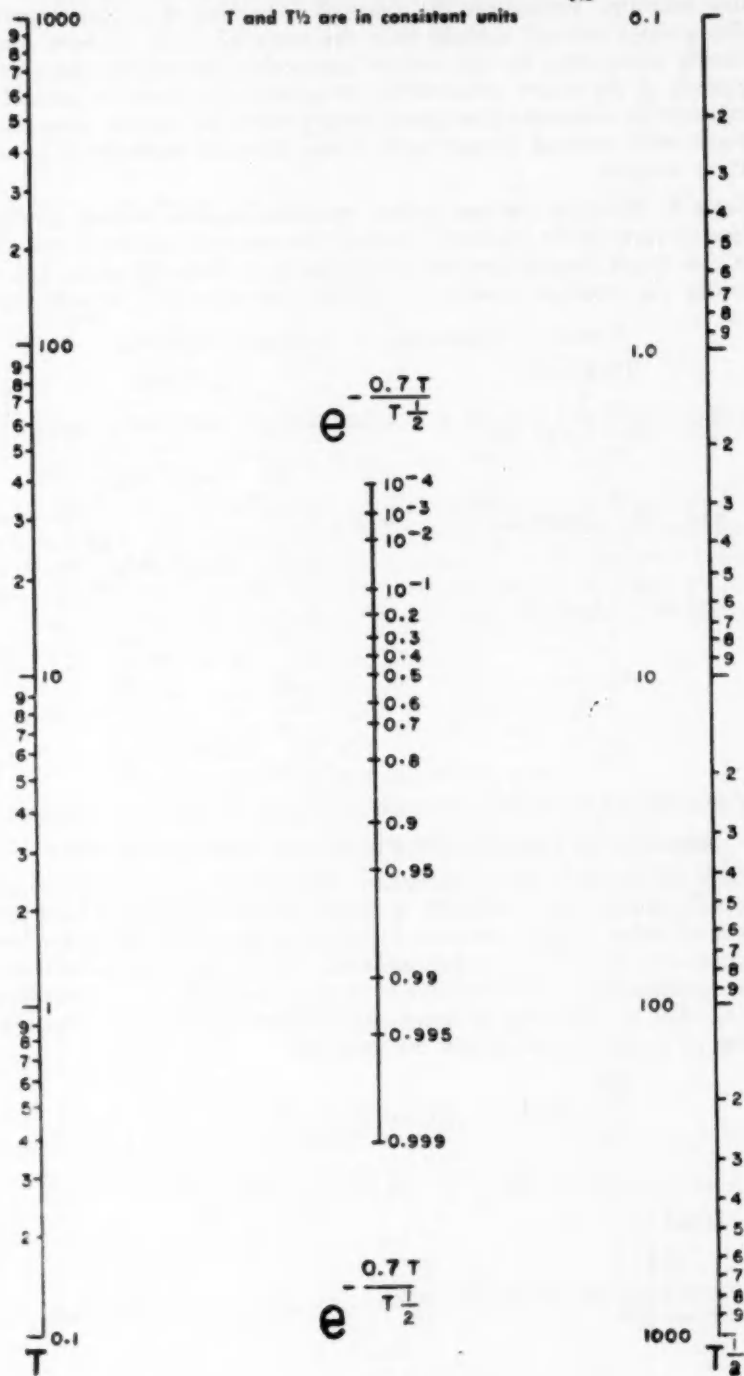
$$N_v = \frac{CA}{W}$$

Some further explanations of this equation are necessary.

Naturally occurring magnesium, for example, is composed of

Mg^{24}	78.60	abundance	percent
Mg^{25}	10.11	"	"
Mg^{26}	11.29	"	"

Fig. 1 Nomogram for Radioactive Decay Term $e^{-\frac{0.7 T}{T_{1/2}}}$ where
 T and $T_{1/2}$ are in consistent units



The activation cross section, σ_a , is different for each isotope. Each must therefore be evaluated when doing a calculation on a commercial magnesium mixture. Frequently the chemical impurities of a "pure" material exhibit greater induced activity than the material itself. A barn may be physically interpreted for the readers' comprehension only as the order of magnitude of the target presented by the atom; σ_a is however, actually an experimentally obtained value representing a statistical capture cross section. It varies with neutron energy⁸ and shows abnormal increases at so-called resonant energies.

Table II illustrates various nuclear reactions possible without specifying the energy level of the neutrons involved; the neutron striking energy level upon the target element determines the reaction that will occur and consequently the resulting amount of radioactivity that will be contributed.

NEUTRON REACTION AT VARIOUS ENERGIES

THERMAL		FAST	
(a)	${}_{13}^{27}\text{Al} (n,g) {}_{13}^{28}\text{Al}$	(a)	Inelastic scattering (n,ng)
(b)	${}_{7}^{14}\text{N} (n,p) {}_{6}^{14}\text{C}$	(b)	$\left\{ \begin{array}{l} {}_{13}^{27}\text{Al} (n,p) {}_{12}^{27}\text{Mg} \\ {}_{26}^{56}\text{Fe} (n,p) {}_{25}^{56}\text{Mn} \end{array} \right\}$
(c)	${}_{5}^{10}\text{B} (n,\alpha) {}_{3}^7\text{Li}$	(c)	${}_{11}^{24}\text{Na} (n,\infty) {}_{11}^{24}\text{Al}$
		(d)	${}_{13}^{27}\text{Al} (n,2n) {}_{13}^{26}\text{Al}$

Note that the (n,p) reaction is usually induced only by fast neutrons.

FORMATION OF INDUCED RADIOACTIVITY WITH SIMULTANEOUS DECAY

While the water is being bombarded with neutrons in the reactor, the activated atoms are simultaneously decaying as indicated above. In order to know the number of active atoms in existence at the instant the water leaves a reactor, this decay must be accounted for. If the half-life of the element under consideration is short relative to neutron bombardment or irradiation time, t_i , then the influence of decay is of greater significance. The rate of increase of a radioisotope is now expressed as

$$\frac{dN}{dt} = P - \lambda N = P + D$$

$$\text{let } u = P - \lambda N \quad du = -\lambda dN$$

Then

$$\frac{dN}{P - \lambda N} = dt = -\frac{du}{\lambda u}$$

and

$$- \ln u \left] \frac{P - \lambda N}{P} - \lambda dt \right]_0^{t_1}$$

$$- \ln \frac{(P - \lambda N)}{P} = \lambda t_1$$

$$\frac{P - \lambda N}{P} = e^{-\lambda t_1}$$

$$P (1 - e^{-\lambda t_1}) = \lambda N$$

Finally

$$N = P \frac{(1 - e^{-\lambda t_1})}{\lambda}$$

where N is the number of active atoms at time of cessation of irradiation.

$$\text{At } t_1 = \infty \quad N = P/\lambda$$

This condition is called saturation, i.e. the radioactive atoms are being produced as fast as they are decaying. This equation is valid for any experimental and structural material in the pile as well as for water. After the water passes the neutron bombardment section, production ceases but decay continues. For any time after neutron irradiation, say t_e , the equation becomes:

$$N = \frac{(nv) (\sigma) (N_v) (1 - e^{-\lambda t_1}) e^{-\lambda t_e}}{\lambda}$$

IRRADIATION OVER NUMEROUS CYCLES

However, the above equation only represents the number of atoms in the water activated per unit time with one pass through the active neutron bombardment section of the pile. For n passes or cycles, the following equations are developed. Allowing K , a constant, to be defined by

$$K = (nv) (\sigma) (N_v) (1 - e^{-\lambda t_1}) \div \lambda$$

$$\text{1st pass} \quad N_1 = K$$

$$\text{2nd pass} \quad N_2 = N_1 a + K = Ka + K$$

where

$$a = e^{-\lambda t_e}$$

$$\text{3rd pass} \quad N_3 = N_2 a + K = Ka^2 + Ka + K = K(a^2 + a + 1)$$

$$\text{nth pass} \quad N_n = (N_{n-1}) a + K = K(a^{n-1} + a^{n-2} + \dots + 1)$$

$$\text{or} \quad N_n = \frac{K(1 - a^n)}{1 - a}$$

As n approaches infinity, N_n will approach a maximum saturation value.

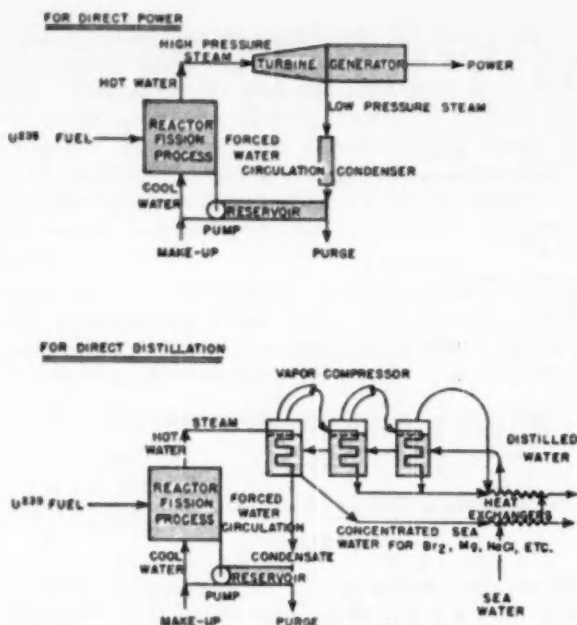


Fig. 2 Direct application reactor heat energy in water cycle

Another way to look at this is to note the amount of decay per cycle as $N-Na$, then the change in N per cycle is

$$\frac{dN}{dn} = N_1 - (N-Na) = N_1 - Na'$$

where

$$a' = 1 - a$$

Integrating over n cycles with N_1 and a' as constants

$$\int \frac{dN}{N_1 - Na'} = \int dn \text{ or } -\frac{1}{a'} \ln (N_1 - Na') = n + \text{Constant}$$

$$N_1 - Na' = Ce^{-a'n}$$

but at $n = 0$, $N = 0$ and $N_1 = C$, hence

$$Na' = \frac{N_1 (1 - e^{-a'n})}{a'}$$

N increases with the number of cycles, n . Equilibrium activity is achieved when $a'n$ is large and $N = N_1/a'$. Under the equilibrium circumstances the number of new radioactive atoms produced per cycle just equals the number of old ones decaying per cycle. The smaller the ratio of isotope half-life to cycle time (less than 1:10), the more quickly the activity saturates.

For values of $\frac{t_1}{t_{1/2}}$ and $\frac{t_c}{t_{1/2}}$ smaller than 0.01,

$$N = \frac{(nv) (\sigma) (N_v) t_1}{t_0} \text{ and } N \text{ is independent of half life as}$$

as deduced from N which is

$$\frac{[(nv) (\sigma) (N_v) (1 - e^{-.7 t_1/t_{1/2}})] [(1 - e^{-n (1 - e^{-.7 t_0/t_{1/2}})])]}{1 - e^{-.7 t_0/t_{1/2}}}$$

ASSUMPTIONS

An original presumption for all these equations is that the values to be substituted are known with accuracy. This is frequently not the case. The distribution of energy among the neutrons in a given reactor is not known accurately and since the neutron absorption cross section is related to it in addition to the factor of resonance interference, an overall uncertainty in the formulation of the energy of the neutrons exists. A further assumption is made that the concentration of the isotope being bombarded does not change. This however is quite valid for most cases. Its dependence on other equation factors may be realized from the small number of atoms activated. (See the sample Problem.) There is an original number of molecules under bombardment of the order of 10^{23} , or 10^{17} if we speak of parts per million per milliliter. Only 10^{-24} of these can be hit, because that is the order of magnitude of the neutron absorption cross section. The flux will be of the order of 10^{13} (see references 1 and 6) and the decay term will depend on the isotope half life and pile neutron bombardment time. If the water cycle takes the order of minutes, while irradiation time takes only fractions of seconds, then the ratio of the cycle time to irradiation time is of the order of many hundreds or thousands. The ratio of time of irradiation to the time of most isotope half lives will probably be even smaller in the decay exponential term $(1 - e^{-\lambda t_1})$ with the result that the decay will be small during the cycle period (see sample calculations for Na^{24}). For values of λt greater than 5, $(1 - e^{-\lambda t})$ is practically one; e.g. at $\lambda t = 5$, $(1 - e^{-\lambda t}) = 0.993$. For values smaller than 0.01, $(1 - e^{-\lambda t})$ is equal to λt ; at $\lambda t = 0.01$, $(1 - e^{-\lambda t}) = 0.01$. For convenience in making these calculations involving the exponential term:

- The accompanying nomograph, Fig. 1, has been prepared.
- The *Nomograph for Materials Irradiation* can be procured (see reference 6).
- The circular slide rule ISOTOPE CALCULATOR can be procured from the author of reference 6.
- A special linear slide rule can be prepared.

PILE COOLING WATER WITH CLOSED CYCLE AND PURGE

The most logical design of a cooling water system for future reactors consists of a closed cycle of recirculation with a small percentage of purge and make-up in order to control the intensity of long lived induced activity and the accumulation of corrosion products. Two possible applications, requiring such a system are illustrated in Figure 2. One proposal is the utilization of flash evaporation in a reactor to drive a turbine directly; the

other is for the recovery of potable water from sea water. The method of obtaining purge and make-up can be varied. Fresh water can be added as circulating water is removed. A small per cent of cycling water can be passed through filters and deionizers and can then be returned to the system. Similarly a side stream could be distilled either by simple evaporation or by a vapor compression still. Some sort of degassing will be necessary at all times, because hydrogen and oxygen gases are formed in the water from the absorption of gamma rays. This radiant gamma energy constitutes about 10% of pile power output and about 100 electron volts are required to

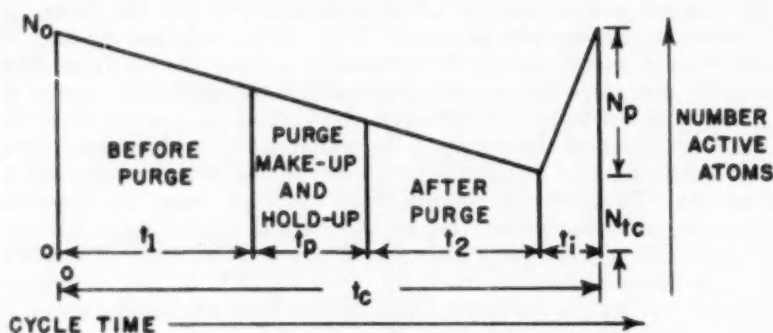


Fig. 3 Diagram representing conditions in a recirculation system

liberate one hydrogen molecule³. The ionizing rays also cause about 30 ppm H_2O_2 to be formed in equilibrium with the liberated hydrogen.

When a recirculation system is used, regardless of the method used for purge and make-up, the number of radioactive atoms at radiation equilibrium (at saturation where production equals decay) must be presented by a different formulation as identified by Fig. 3 and the following itemized nomenclature.

N_o is the number of active atoms in the water leaving the pile immediately after neutron irradiation.

N_p is the number of atoms activated in the pile during irradiation time, t_i .

t_1 is the (decay) time starting when the water leaves the pile and ending when the water arrives at a hold-up tank in the cycle. It is from this hold-up tank that purge occurs to minimize radioactivity and total dissolved solids in the water. Make-up water is added in the same tank.

t_2 is the (decay) time elapsed until the water once more enters the pile from the hold-up tank.

N_{tc} is the number of active atoms at the end of the cycle and just before another irradiation.

The following equations can now be derived:

$$N_o = N_p + N_{tc}$$

where t_1 and t_p are negligible relative to t_c , hence

$$t_p = t_1 + t_2$$

and Y = main water circulating rate
and y = purge and make-up water rates
hence,

$$N_{te} = \frac{Y}{Y + y} N_0 e^{-\lambda t_e}$$

and by solving for N_p in terms of N_0

$$N_p = N_0 \left(1 - \frac{Y}{Y - y} e^{-\lambda t_e} \right)$$

From the fundamental decay equation

$$N_t = N_0 e^{-\lambda t}$$

where t = any time up to t_1 or t_2 for each equation developed for the period before purge or after purge.

The number of active atoms before purge are

$$N_t = \left[\frac{N_p}{1 - \frac{Y}{Y + y} e^{-\lambda t_e}} \right] e^{-\lambda t}$$

The number of active atoms after purge are

$$N_t = \frac{Y}{Y + y} \left[\frac{N_p}{1 - \frac{Y}{Y + y} e^{-\lambda t_e}} \right] e^{-\lambda t}$$

SOURCES OF RADIOACTIVITY IN WATER

The formulas presented above are used to calculate the amount of activity induced in water. Elements and sources which will contribute to the water activity can be listed under the following categories:

- 1) Isotopes of oxygen in the water itself.
- 2) Solutes in the water such as mineral impurities or dissolved oxygen.
- 3) Radioactive elements corroded from structures in the reactor.
- 4) Radioactive elements knocked into the water by recoil upon the instant of neutron capture.

These will be discussed briefly in the following paragraphs and will be further clarified by the sample calculations at the end of the article.

If one has perfectly pure water with no dissolved solids, the water will become radioactive due to neutron capture by the isotopic mixture of oxygen in natural water. This is illustrated by the following table:

Per Cent Abundance	Reaction	$t_{1/2}$ Seconds
99.757	$O_8^{16} + n \rightarrow N_7^{16} + p$	8
0.204	$O_8^{18} + n \rightarrow O_8^{19} + g$	27
0.039	$O_8^{17} + n \rightarrow O_8^{18}$	stable

These substances, being most abundant, produce an enormous amount of

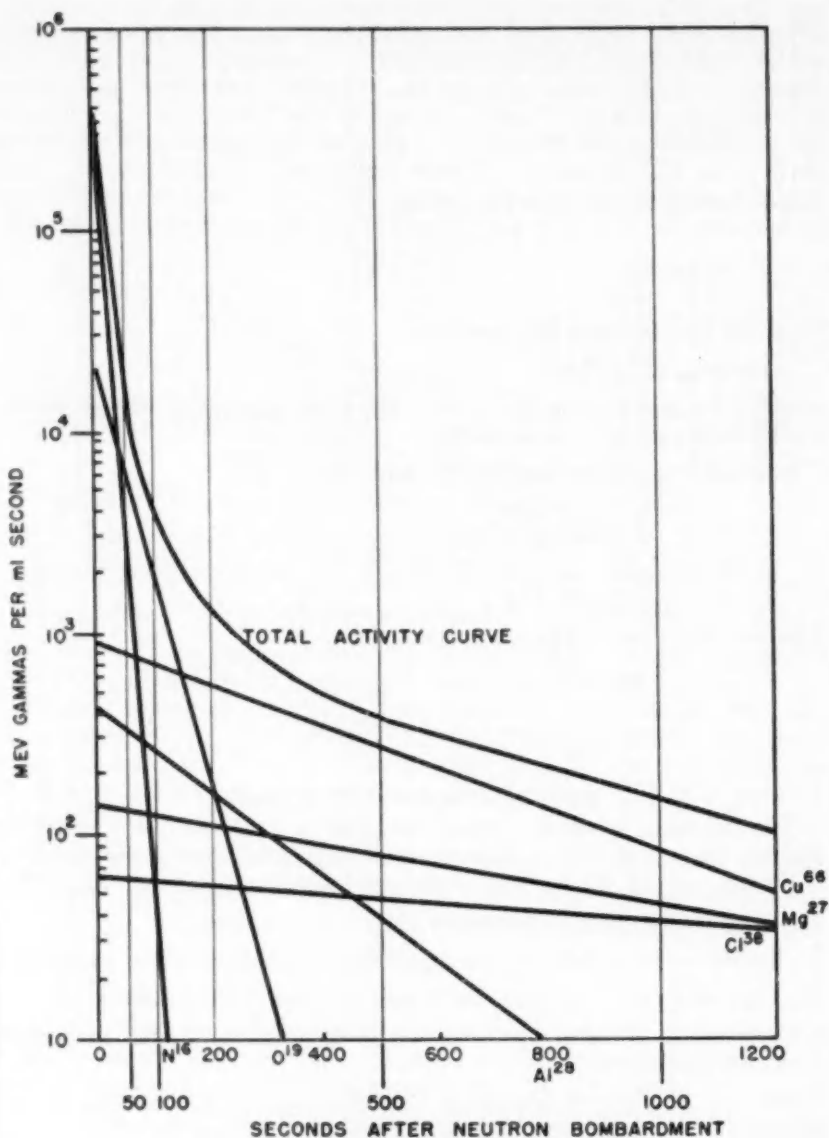


Fig. 4 Decay of Reactor Cooling Water Activity
(Hypothetical Case)

Log Mev gamma per cc-sec vs Decay Time in seconds
One second exposure to 10^{18} neutron flux
Water Content
 $O^{16} \times 16/18 = 0.89$ grams per ml
 $O^{18} \times 16/18 = 0.002$ grams per ml
Hydrogen is inactive

	N^{16}	O^{18}	Al^{28}	Cu^{66}	Mg^{27}	Cl^{36}	Na^{24}
Mev Gammas	4	1.6	1.8	1.3	1	2.2	1.4 , 2.8
T $\frac{1}{2}$ Seconds	8	27	144	300	690	2200	53000
Each 1 pper							

activity but lose their controlling influence in about one minute because of their short half-lives. This is the primary source of induced radioactivity in water.

Activity in the water is contributed not only from neutron bombardment of the dissolved elements in the water originally, but also from those elements corroded into the water from the piping system. The activity contributed by each ion will depend at a fixed water flow and flux on its absorption cross section, concentration, resonance characteristics, atomic weight and product half life. This is the main secondary source of water activity and, depending on the activated ions, is usually long lived, that is, a matter of hours, days, months or even years.

Metallic elements in the reactor structure capture neutrons and some become radioactive and change during decay to isotopes of the same or different elements. The introduction of these activated ions into the water stream is called recoil.

Induced water activity data can be presented by plotting on semi-log paper the log of water activity in Millions of electron volts (Mev) gammas per milliliter-second as ordinate and the decay time in seconds for each element as abscissa. A straight decay line results for each constituent of the water. A summation of all these activities will yield a curve of over-all activity. The relative position of the individual lines indicates which constituents at a particular time are the radio-isotopes most greatly contributing to the over-all activity. Figure 4 presents a typical example of these curves; it is derived for a hypothetical case based on several typical natural water constituents. Table II lists the calculated values plotted in Fig. 4.

SAMPLE PROBLEM

In order to illustrate the application of the formulas presented in this article, the following problem is proposed:

- Calculate the number of active Na^{24} atoms per milliliter of water immediately after neutron bombardment at a hypothetical 10^{18} flux after one second irradiation. The absorption cross section of Na^{23} is 0.4 barns for thermal neutrons. There is one part per million Na^{23} in the water. The half life for Na^{24} is 14.8 hr.
- Calculate the number of active Na^{24} atoms per milliliter of water 50, 100, 500 and 1,000 sec. after one second irradiation.
- Calculate the decay in number of disintegrations of Na^{24} per milliliter of water per sec. at 0, 50, 100, 500 and 1000 sec.
- Determine the release of disintegrating energy in Mev/ml-sec 0 seconds after irradiation.

SOLUTION

$$\begin{aligned}
 \text{a) } N &= 10^{18} \times 0.4 \times 10^{-24} \times \frac{10^{-6} \times 6 \times 10^{23}}{23} \times \frac{1 - e^{-\frac{0.7 \times 1}{14.8 \times 3,600}}}{1} \\
 &\div \frac{0.7}{14.8 \times 3,600} \\
 &= \text{flux} \times \text{cross section} \times N_v \times \text{decay term} \div \lambda \\
 &= 10^6 \text{ active } \text{Na}^{24} \text{ atoms per ml at 0 seconds}
 \end{aligned}$$

$$b) \quad N_t = N_0 e^{-\lambda t}$$

$$N_{50} = 10^5 e^{-\lambda 50} = 10^5 \times \frac{1}{1.001} =$$

$$N_{100} = \quad \quad \quad \times \frac{1}{1.002} =$$

$$N_{500} = \quad \quad \quad \times \frac{1}{1.010} =$$

$$N_{1000} = \quad \quad \quad \times \frac{1}{1.025} =$$

$$c) \quad D = \frac{dN}{dt} = \lambda N$$

$$D_0 = 1.3 \times 10^{-5} \times 10^5 = 1.3 \text{ disintegrations/ml-sec}$$

$$D_{50} = \quad \times N_{50} =$$

$$D_{100} = \quad \times N_{100} =$$

$$D_{500} = \quad \times N_{500} =$$

$$D_{1000} = \quad \times N_{1000} =$$

- d) Each disintegration of Na^{24} releases a 1.4 Mev and a 2.8 Mev gamma ray, hence

$$1.3 \text{ dis/ml-sec} \times (1.4 + 2.8) \frac{\text{Mev}}{\text{dis}} = 5.5 \text{ Mev/ml-sec}$$

The calculations for the results tabulated are somewhat tedious and liable to human error when calculating radioactivities for many constituents. The use of prepared nomographs⁶ or a special circular or linear slide rule facilitates the calculations and minimizes the possibilities of error.

Finally Table II lists the results of a more complete calculation for a once-through cooling water based on a hypothetical case of 10^{13} neutrons per sq cm per sec flux and one ppm of each element present in the water.

WATER ACTIVITY AND ITS RADIATIONS

Radiation from radioactive water sources depends on the concentration and kinds of active isotopes present, the quantity of active water, the size, shape or geometry of the water active source, how it surrounds the observer and how much radiation is self-absorbed by the source. In order to understand and gain an insight into the order of magnitudes of radioactivity that can occur, the term of atomic disintegrations during decay per milliliter per second is usually spoken of as curies per milliliter. One curie is defined⁸ as the activity of the radon which is present in equilibrium with one gram of radium. The same unit is applied to artificially produced radioactive substances and is further defined as the activity of any substance in which 3.7×10^{10} atoms disintegrate per second. Maximum Permissible

Contamination for water, MPC, is $10^{-7} \frac{\text{micro curies}}{\text{ml water}}$ and any discharges

TABLE II

ILLUSTRATION OF ARBITRARY CALCULATIONS ON REACTOR NEUTRON INDUCED COOLING WATER ACTIVITIES

for purposes of this example we can assume a flux of 10^{13} and 1 ppm of each of the indicated dissolved elements.

One Cycle—Seconds After Neutron Bombardment																				
Target	Isotope	Reaction	Product	Isotope	Half life	$\lambda \left\{ \begin{array}{l} \text{sec}^{-1} \\ 0.693 \\ \text{hr} \end{array} \right.$	Fraction	Barns 10^{-28} cm^2	N_0	Decay Factor $(1 - \lambda t)$	Disintegrations/cc-sec		γ		β Mev	β Mev	β Mev			
											0	5×10^{-8}	0	1000						
0 16	16 8					0.087	0.89	< 0.001	6×10^{12}	0.100	5×10^{-8}	75	0	0	6.9	35×10^4	35	0	4	
0 18	18 0					0.022	0.002	0.0002×10^{26}	0.8×10^{17}	0.030	500	0	4.1	20×10^8	6000	2000	0	1.6		
0 28	28 0					0.005	10^{-6}	0.2	0.25×10^{17}	5×10^{-6}	180	150	25	2	1.8	450	320	270	45	4
Al 27	Al 28					0.002	3	0.1	0.1×10^{17}	2.3×10^{-6}	600	560	230	70	1.3	910	780	730	300	90
Cu 65	Cu 66					0.001	"	0.08	0.25×10^{17}	7×10^{-6}	140	135	84	50	1	140	135	125	84	50
Mg 26	Mg 27					3×10^{-10}	"	0.6	0.16×10^{17}	3×10^{-6}	30	29.5	29	25	2.1	63	62	60	52	45
Cl 37	Cl 38					2×10^{-10}	"	0.9	0.1×10^{17}	"	"	"	"	"	"	"	"	"	"	"
Zn 68	Zn 69					2×10^{-10}	"	1.3	0.1×10^{17}	"	"	"	"	"	"	"	"	"	"	"
Mn 55	Mn 56					0.8×10^{-10}	"	0.1	0.2×10^{17}	"	"	"	"	"	"	"	"	"	"	"
Si 31	Si 32					0.7×10^{-10}	"	0.1	0.2×10^{17}	"	"	"	"	"	"	"	"	"	"	"
A 41	A 42					1.1×10^{-10}	"	1.2	0.14×10^{17}	"	"	"	"	"	"	"	"	"	"	"
A 40	A 41					0.8×10^{-10}	"	2.6	0.1×10^{17}	"	"	"	"	"	"	"	"	"	"	"
Ni 64	Ni 65					1.5×10^{-10}	"	1.0	0.14×10^{17}	"	"	"	"	"	"	"	"	"	"	"
K 41	K 42					1.3×10^{-10}	"	0.4	0.25×10^{17}	1.3×10^{-6}	1.3	1.3	1.3	1.3	1.4	5%	5%	5%	5%	5%
Na 23	Na 24					3×10^{-10}	"	11	0.11×10^{17}	"	"	"	"	"	"	"	"	"	"	"
Cr 50	Cr 51					2×10^{-10}	"	0.01	"	"	"	"	"	"	"	"	"	"	"	"
H 1	H 2					1×10^{-10}	"	3500	"	"	"	"	"	"	"	"	"	"	"	"
Be 9	Be 10					1×10^{-10}	"	24000	"	"	"	"	"	"	"	"	"	"	"	"
B 10	B 11					7×10^{-10}	"	0.6	"	"	"	"	"	"	"	"	"	"	"	"
Cd 113	Cd 114					1×10^{-10}	"	0.1	"	"	"	"	"	"	"	"	"	"	"	"
Ca 44	Ca 45					2.4×10^{-10}	"	0.1	"	"	"	"	"	"	"	"	"	"	"	"
C 13	C 14					1.5×10^{-10}	"	0.1	"	"	"	"	"	"	"	"	"	"	"	"
F 19	F 20					1.5×10^{-10}	"	0.01	"	"	"	"	"	"	"	"	"	"	"	"
Fe 56	Fe 57					2.9×10^{-10}	"	2.9	"	"	"	"	"	"	"	"	"	"	"	"
N 14	N 15					3.4×10^{-10}	"	0.3	"	"	"	"	"	"	"	"	"	"	"	"
S 34	S 35					0.8×10^{-10}	"	0.2	"	"	"	"	"	"	"	"	"	"	"	"
P 31	P 32					1.2×10^{-10}	"	0.2	"	"	"	"	"	"	"	"	"	"	"	"
TOTAL													37×10^8	11×10^8	3700	480	200			

* Actually high energy neutron required

n, neutron; p, proton; γ , γ . γ , gamma; ∞ , alpha; β , beta

from "atomic plants" are kept below this activity level. For gamma radiation the same dose unit is used as for X-rays, i.e. the roentgen. The two units curie and roentgen are fundamentally different since the former defines a property of the radiating element while the latter is defined on the basis of the arbitrary selection of air as the absorber of gamma ray energy thus giving an indication regarding the biological effect of the gamma rays present.

"The roentgen unit (r)⁷ is that quantity of X-ray or gamma radiation such that the associated corpuscular emission per 0.001293 gm of air (1 cc dry air at 0°C and 760 mm Hg) produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign." 3×10^9 e.s.u. = coulomb.

A milligram of Ra in equilibrium with its decay products yields about 8.4 r per 8 hr at a distance of one cm when filtered with a half mm platinum foil⁴. This unit of r was chosen since it is relatively easy to measure the ionization of air or gases and then to find its physiological equivalence to human and animal tolerances by experiment. Since 4.8×10^{-10} e.s.u. = electron ion charge or 2.083×10^9 ion pairs, one r produces

$$\frac{2.083 \times 10^9}{0.001293} = 1.61 \times 10^{12} \frac{\text{ion pairs}}{\text{gm air}}$$

"If an average of 32.5 electron volts (ev) are expended to form each ion pair in air, then one r corresponds to the absorption of 5.24×10^{13} ev of energy (or 5.24×10^{13} ev $\times \frac{\text{erg}}{6.25 \times 10^{11} \text{ ev}} = 83.8$ ergs) per gram of

air." Workers (essentially composed of water) exposed to radiation continually are protected so that they receive not more than 50 mr per 8 hr day or 0.3 roentgen per week. However, a dose of 10 roentgens for a short period will not kill a person, but 400 roentgens may kill about $\frac{1}{2}$ of those exposed. Water has about 1000 times the photon absorption coefficient (also density) of air.

ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance and recommendations made by numerous individuals both at Oak Ridge and Argonne National Laboratories in preparing this manuscript.

1. "Introduction to Radio Chemistry," by Friedlander and Kennedy—Wiley, 1949.
2. AECD 2138 "Thermal Neutron Cross Sections for Elements and Isotopes, H-Bi," by Way and Haines, Oak Ridge, Tenn., 10-11-49.
3. "The Science and Engineering of Nuclear Power"—Edited by C. Goodman, Addison-Wesley Press, Inc., Cambridge, 1947, Vol. I, II.
4. "Nuclear Radiation Physics," by R. E. Lapp and H. L. Andrews, Prentice-Hall, January 1949.
5. "Safe Handling of Radioactive Isotopes," September 1949, National Bureau of Standards Handbook 42.
6. NUCLEONICS, January 1950, "Nomograph for Materials Irradiation," by C. M. Clear.
7. NUCLEONICS, Vol. 1, No. 2, pages 32-43, October 1947, "Radioactivity Units and Standards," by R. D. Evans.
8. "Introduction to Atomic Physics," by Otto Oldenberg, McGraw-Hill, 1949.
9. "Research on the Disposal of Radioactive Wastes," by O. R. Placak and R. J. Morton, J.A.W.W.A., Vol. 42, No. 2, February 1950.
10. Bulletin National Research Council, March 1929, No. 51, Vol. 10, *Radioactivity*, by A. F. Koverik and L. W. McKeenham, National Academy of Sciences, Washington, D. C.

Nuclear Power Engineering

Part XII. Energy relations in the fission process . . .
Conditions necessary for fission . . . The mechanism of
induced fission . . . Calculation of binding energy . . .
Distribution of fission products . . . Energy balance for
the fission process . . . The emission of delayed neutrons
and their significance in the design of nuclear reactors

By **ANDREW W. KRAMER**

FROM OUR DETAILED consideration of the liquid-drop model of the nucleus in the last chapter it is evident that as the size of a nucleus increases the amount of energy needed to cause the nucleus to undergo fission decreases. In the liquid drop model, the original nucleus is assumed to be spherical. When energy is fed into this spherical nucleus, it begins to deform and vibrate like a drop of liquid. Assuming that the sphere becomes slightly ellipsoidal there will be a change in both the surface energy and the Coulomb (electrical) energy. The surface energy will be changed in proportion to the increase in surface area. The elongation of the nucleus pulls the protons apart, causing a decrease in their mutual repulsion. The two effects cancel each other to some extent but in large nuclei the electrical forces are stronger relative to the surface forces than in light nuclei so that such large nuclei are unstable and undergo spontaneous fission with the slightest addition of energy.

Figure 1 is a curve showing the binding energy of the nuclei. This curve shows the relation of the surface (tension) forces and the Coulomb (electrical) forces to the atomic weight A of the nuclei. Because of the greater Coulomb repulsion the heavy nuclei have less binding energy than the nuclei of medium atomic weight. If this curve was drawn more precisely it would show that it is energetically possible for all nuclei above atomic weight 100 to transform into middle size nuclei. When, large nuclei break into two such fragments, the process is called fission.

We have already studied the possible mechanism of this fission process but it will be of advantage to consider the process with respect to the actual elements, that is, with respect to the atomic weight of the elements. The curve shown in Fig. 2 shows the Coulomb energy E_c and the symmetrical fission (where the heavy nucleus splits into two equal fragments) energy E_0 with respect to the atomic weight A . E_0 is the energy released in fission in Mev. This energy begins to have a positive value when A reaches a value of approximately 85 and it increases as the atomic weights increase.

The reason that only the heaviest nuclei undergo fission is that there is an activation energy for this reaction, that is, a certain activation energy is required to initiate the process. This is shown in Fig. 3. If E represents the potential energy of the nucleus or of the fragments of a nucleus, as a function of the distance r between the centers of the two parts, it is evident that for large r , the energy is simply the electrostatic energy resulting from the mutual attraction of the two positively charged nuclear fragments. The value of E in this region is $(Ze/2)^2 \div r$, where Z is the

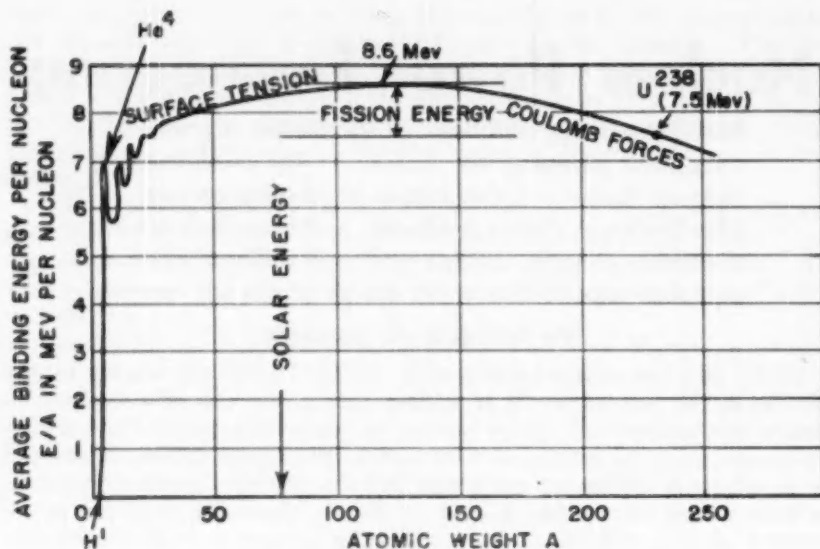


Fig. 1 The binding energy of Nuclei

atomic number, e the electronic charge and r the distance between the parts. Thus, the value of E increases as the distance between the two fragments is decreased. Where r is infinity, the energy is considered zero. Where r is less than $2R$, (twice the radius of each fragment assumed to be spherical) the energy will no longer be simply Coulombian since there will be other forces between the fragments. The curve must pass through the point corresponding to the energy of the coalesced nucleus E_0 , when $r = 0$.

The curves in Fig. 3 show three possibilities. Curve I is for stable nuclei with atomic weights of somewhat less than 100, with E_0 less than E_c , the Coulomb energy at $r = 2R$. The variation of E_c with the atomic weight A is shown in Fig. 2. The difference in $E_c - E_0$ for such nuclei is about 50 Mev and is known as the energy barrier height against splitting.

Curve II is for nuclei such as uranium, thorium, plutonium, where the difference between E_c and E_0 is about 6 Mev. For still heavier nuclei, E_0 (the fission energy) may be less than E_c (the Coulomb energy) and such nuclei would certainly undergo fission spontaneously. For this reason they can not exist long in nature. The nonexistent transuranic elements are probably of this type.

Considered on a purely classical basis, nuclei of the type shown by curve II are entirely stable but from the quantum standpoint there is a certain probability that such nuclei will undergo spontaneous fission and this probability increases rapidly with decreasing $E_c - E_0$. Only where the atomic weight is greater than about 220 is the barrier height small enough for spontaneous fission to occur with any reasonable probability. Uranium 238 for example undergoes spontaneous fission at the rate of about 20 disintegrations per gram per hour. This corresponds to a half life around 10^{17} years.

Another way of looking at the energy relations existing in different nuclei is by likening the process to rolling marbles into a small V-shaped well

with a small ridge around it. If we start rolling marbles (Neutrons) into it, they will first roll in easily and will do work (release energy) as they fall in.

When the well is filled about level, they will just roll in without releasing or requiring any work. From then on, however, it will be necessary to put some work in, in order to stack them up, until finally a point is reached where no more can be added without having them roll off.

It will be obvious that this is analogous to the behavior of nuclei of increasing mass. The first case corresponds to one of the light elements, say, helium. The second case might represent an element in the middle of the periodic table, iron or copper for example. The last case is where we have a heavy element such as uranium.

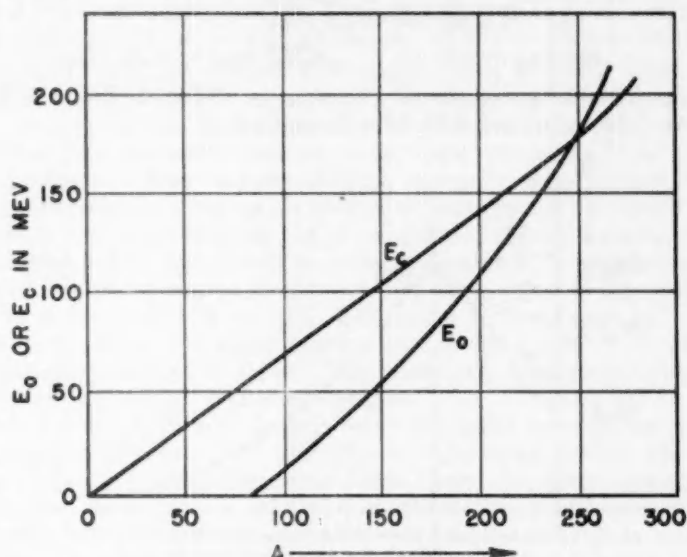


Fig. 2 Coulomb energy E_c and symmetrical fission energy E_0 versus atomic weight

Thus, energy can be obtained in two ways: first, by building up some of the lighter elements, by rolling marbles into the well, or second, by breaking down heavier ones, by making the marbles roll down off the hill. The first process is equivalent to that of combustion whereas the second is equivalent to setting off a charge of TNT.

INDUCED FISSION

The necessary excitation energy $E_c - E_0$ required to induce fission in nuclei of the type II (Fig. 2) can be provided in a number of different ways. As already shown, we can accelerate charged particles such as protons, alpha particles, deuterons, electrons by electric potentials and bombard nuclei with them. Energy can also be imparted by radiation in the form of gamma rays. Finally, neutrons can be used to induce fission.

In the design and operation of nuclear reactors, only neutrons and to a lesser extent, gamma rays, are of importance in inducing fission. Where gamma rays induce fission the threshold energy is around 5 Mev and since

few of the fission or fission product gamma radiations have energies greater than 5 Mev, photofission does not account for a significant proportion of the fissions produced in nuclear reactors. This, therefore, leaves neutron induced fission as the important factor in the operation of nuclear reactors. Neutrons contribute both their kinetic energy and their binding energy to the nucleus. The binding energy of a neutron to a particular nucleus can be calculated quite simply, as shown in the following calculation for the binding energy of a neutron to U 235. M = the precise atomic mass of the particle.

$$\begin{array}{rcl}
 M(\text{U-235}) & = & 235.11240 \\
 M(n) & = & 1.00893 \\
 \hline
 M(\text{U-235} + n) & = & 236.12133 \\
 M(\text{U-236}) & = & 236.11401 \\
 \hline
 \text{Binding energy} & = & .00732 \text{ amu} = 6.81 \text{ Mev}
 \end{array}$$

similarly, the binding energies of a neutron to U-236, U-237, and U-238, would be 5.51, 6.56, and 5.31 Mev respectively.¹

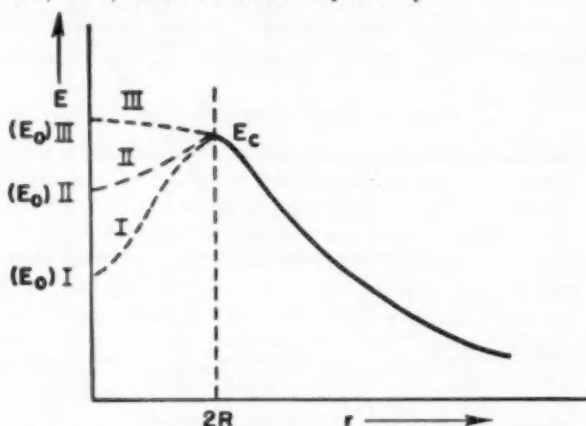


Fig. 3 Curve showing the nuclear energy E as a function of the distance r between fission fragments

It has been found that the binding energy of neutrons to nuclei of odd A/Z (ratio of total nucleons to protons) such as U-235 and U-237 is larger than for even A/Z , such as U-236 and U-238. It has been suggested that the nucleons tend to fall in the lowest nuclear energy levels and that strong forces exist between pairs of neutrons or protons that can fill the same level.

Thus fission with thermal neutrons (very low contribution of kinetic energy) is more prevalent in nuclei with an odd number of neutrons ($A-Z$ odd). Thermal neutrons on U-235, for example, contribute an excitation energy of 6.8 Mev which is sufficient to carry the compound nucleus U-236 over the potential barrier and produce fission. Thermal neutrons on U-238 on the other hand, contribute an excitation energy of only 5.3 Mev, an amount insufficient to carry the compound nucleus U-239 over its po-

¹ For more detailed information on the method of calculating the M values the reader is referred to "The Science and Engineering of Nuclear Power," Volume I, Chapter 2, published by Addison-Wesley Press, Inc., Cambridge, Mass.

tential barrier. To cause fission in U-238, the neutrons must have about 1 Mev of kinetic energy in addition to their binding energy.

In this consideration of the fission process it has been assumed that essentially symmetrical fission takes place, that is, the compound nucleus formed by the addition of a neutron splits up into two approximately fragments. Theory indicates that this symmetrical fission is very probable but in practice it is either very rare or nonexistent. Only by chemical studies of the fission products has evidence of symmetrical fission been found. Very small amounts of ^{46}Pd have been found among the fission products of ^{92}U . Practically all of the fission fragments of nuclear fission are of unequal mass. This pronounced asymmetry is not yet understood. The fission process may occur in many different modes, and a large number of fission products are known, ranging from $Z = 30$ (zinc) to $Z = 36$ (europium) and from $A = 72$ to $A = 158$ for the case of U-235 neutron fission.

Due to the fact that the neutron excess (over protons) required for stability is much greater in the region of the heaviest elements than in the fission product region, the primary fission products have neutron excesses far greater than the stable isotopes of the same elements. These primary fission products achieve stability through successive Beta particle decays; some chains with as many as six successive Beta decays are known.

Figure 4 is a curve showing the yield of fission products plotted against mass number. Two peaks will be noted separated by a very pronounced minimum. For slow neutron fission of U-235 the maxima in the yield curve occur at $A = 95$ and $A = 139$. The fission yield at mass 117 (at the minimum) is about 600 times smaller than at the peaks. This indicates the asymmetry referred to above. The asymmetry appears to become less pronounced with higher excitation energies.

When a heavy nucleus undergoes fission the excess neutrons are released. The neutrons, however, are probably not produced during the actual nuclear splitting. It appears much more likely that these neutrons are emitted from the highly excited fission fragments immediately after splitting takes place. On the average somewhat more than one neutron is emitted per fission fragment. The number of neutrons per fission event averages between two and three.

Studies indicate that the average total kinetic energy of the two fission fragments from U-236 is about 160 Mev. In addition the prompt neutrons have kinetic energies totaling about 5 Mev. If the energy of excitation of the fission fragment immediately after its formation is insufficient to cause emission of a neutron, the nucleus may lose energy by the emission of prompt gamma rays. On the average about 5 Mev is released in this form. Since the fission fragments are invariably radioactive, there is additional release of energy in the form of beta, gamma, and neutrino radiation. On the average each fragment emits 3 Beta particles (electrons). The radioactive energy, about 20 Mev, is released over a period of time following fission.

The neutrons (both prompt and the fraction of a per cent of delayed) released during fission are eventually absorbed either in other fissionable nuclei or in materials of construction of the reactor. The binding energy of these neutrons—about 10 Mev—is released either in the form of gamma radiation or of Beta particles from radioactive decay. The energy of these stray neutrons is of minor significance in the total energy release, but it

becomes of importance if the neutrons are absorbed in other than useful parts of a nuclear reactor.

Summing up the various energies, we have an energy balance for the fission of U-236 as follows:

Fission Fragments . . .	160 Mev
Prompt neutrons . . .	5 Mev
Prompt Gamma radiation . . .	5 Mev
Radioactive series . . .	20 Mev
Absorbed neutrons . . .	10 Mev
Total energy . . .	200 Mev

The emission of delayed neutrons is of minor importance in the energy balance of the fission process since these delayed neutrons involve only 0.61

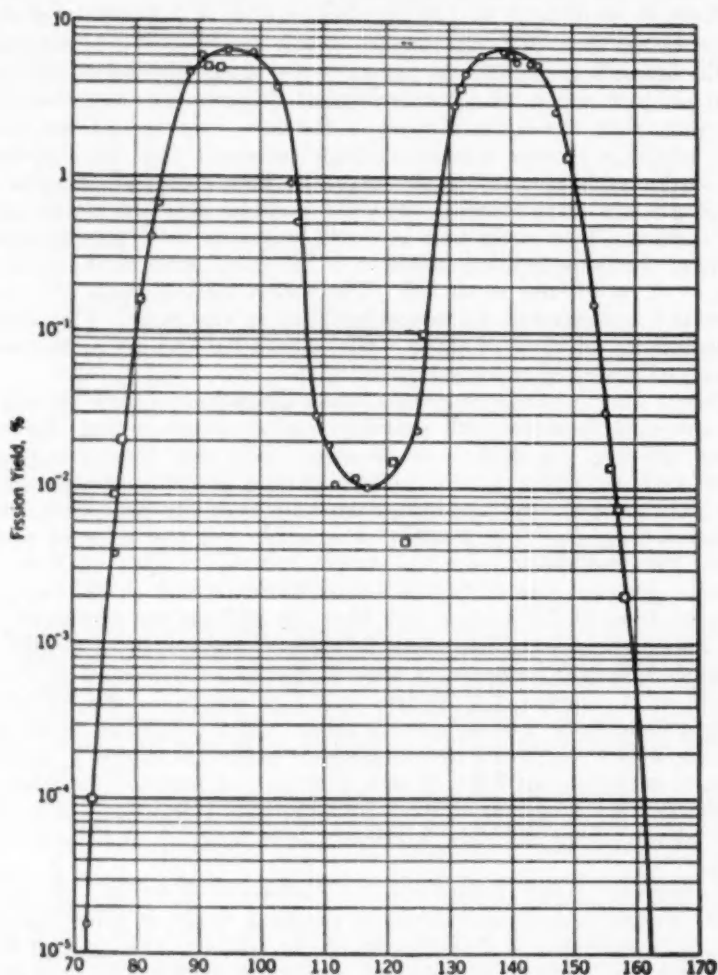


Fig. 4 Yields of fission product chains as a function of mass number in the case of the slow neutron fission of U-235

per cent of the total but they are of great importance in effecting the control of a nuclear reactor. Were it not for these delayed neutrons the extreme rapidity of the nuclear fission reaction would have made it very difficult if not impossible to keep a reactor under control. Knowledge of these delayed neutrons was of tremendous importance in the design of the first nuclear reactor at the University of Chicago. It was realized that this time delay gave a sort of inertia to the chain reaction that should greatly facilitate control. If the effective multiplication factor of a pile became slightly greater than 1, the neutron density would not rise to harmfully large values almost instantly but would rise gradually so that there would be a chance for the controls to operate. The other time intervals such as the controls to operate. The other time intervals such as the time between collisions are too small to be useful. And this proved to be true. By designing a pile such that the effective value of k , the multiplication factor, is only 1.01 the number of delayed neutrons is sufficient to allow easy control.

The delayed neutrons are emitted at various short intervals after fission. So far, about five different delay periods have been measured, these are as follows:

55.6 sec.	0.02
22.0 sec.	0.14
4.51 sec.	0.19
1.53 sec.	0.20
0.42 sec.	0.07
Total	0.61

In the preceding chapters a great many properties of nuclei have been considered. A great many more could be described but the ones considered are the most important in the design of nuclear reactors. For the sake of clarity we will summarize the most important properties as follows:

1. Number of neutrons released on fission. This is not a constant but since a number of reactors have been in successful operation it must obviously be greater than 1. According to the Smyth Report its value is between 1 and 3.

2. Delayed neutrons. Most of the neutrons produced in fission appear at once but a small percentage appear first a short time after fission has taken place.

3. The cross section of nuclear particle. The cross section is a function of the energy of the neutrons which are captured. In some cases, where neutrons are captured by other nuclei cross sections are also a function of resonance.

4. The average logarithmic energy loss suffered by a high-energy neutron in colliding with a nucleus.

5. Although we can hardly consider the numbers of nuclei of various types as properties of the nuclei, the proportions in which we mix nuclei and the total numbers present are always important.

(To be continued)

Atomic Fissions

News From The Atomic World

Nation's Largest Nuclear Reactor for Research Begins Operation at Brookfield

The nation's largest and most powerful research reactor began operating on August 22nd at the Brookhaven National Laboratory. At 2:30 a.m., Dr. Lyle B. Borst, in charge of the reactor for the removal of the control rods, thereby starting the initial chain reaction. Loading of uranium to bring the reactor to its full designed power will continue for several months. Meanwhile, scientific experiments begin, with the reactor operating 24 hours a day.

The Brookhaven reactor is an air-cooled, graphite-uranium pile, which at its designed power level, will develop heat at a rate of 30,000 kw, several times that of the reactor at Oak Ridge. Engineering design and construction were carried out by the H. K. Ferguson Co., acting on scientific specifications established by the Brookhaven reactor staff.

The primary purpose of this reactor is the production of neutrons for scientific experimentation. The arrangement is such as to permit a larger number of simultaneous neutron-using experiments than are possible with any other known reactor. The walls bristle with wiring, tubes, rods, switches and other instruments to aid exacting experiments. One feature



Artist's drawing of the Brookhaven reactor showing the two large windows for illumination

of interest is the system of pneumatic tubes, similar to those used in department stores and banks, for removing samples from the interior of the pile to the various laboratories. This permits operators to whisk samples into and out of the reactor in a matter of seconds.

Operations of the reactor are controlled from a room equipped with a multitude of devices for continually recording the power level, neutron concentration and other operating information essential to the requirements of the operators. Boron control rods control the intensity of the chain reaction. To protect personnel from radiation, the pile itself is surrounded by a shield of concrete several feet thick. Routine precautions include heavy lead shielding, instruments for monitoring radiation levels whenever radioactive materials are handled, and the use of periscopes and remote controls to manipulate highly contaminated substances.

The center section of the building housing the reactor is 72 ft. high and has two windows of green glass 55 ft. tall and 33 ft. wide. It is flanked on both sides by wings containing standard laboratories for technicians. In the specialized Hot Laboratory, the more intensely radioactive products of the pile are chemically processed. Other structures in the reactor group include cooling towers and a fan house as well as a 320-ft. red-and-white stack, all part of the system for handling the large quantities of air for cooling the reactor.

Scientists Measure Longest Known Time Interval and Brief Half-Life of Neutral Meson

The longest time interval ever measured has been reported within recent weeks by atomic scientists at the Argonne National Laboratory, Chicago. At the other end of the time scale, another group of scientists has clocked the life-span of the most ephemeral known sub-atomic particle at the Radiation Laboratory, University of California, Berkeley.

The two newly measured time intervals make a striking contrast. The longer interval is 5×10^{41} (5 followed by 41 zeros) times greater than the smaller.

The half-life of a radioactive species or isotope of the sulfur-like element tellurium, known as tellurium 130, was measured at 1.5 sextillion (15 followed by 20 zeros) years by Dr. Mark G. Ingraham and John Reynolds of the spectroscopy laboratory at Argonne National Laboratory. Up until now tellurium 130 was thought to be a stable or non-radioactive isotope of tellurium.

The shortest half-life, that of the neutral meson emitted in certain types of nuclear reactions, was clocked at one ten-trillionth of a second by a technique developed by Dr. Herbert York at the Radiation Laboratory.

Mesons may have a positive charge, a negative charge, or as recently observed, no charge at all. This last type, called the neutral meson, decays almost as soon as it is formed into two high energy gamma rays.

100 Mev G-E Betatron Installed at University of Chicago

The largest and most powerful commercially available particle accelerator, a 100,000,000 electron volt General Electric betatron, is now installed and being tested at the University of Chicago.

First complete unit of its type ever sold by G.E., the new giant will be used for nuclear research by the staff of the University's Institute for Nuclear Studies which includes Dr. Enrico Fermi who is well known for his work in atomic development.

Engineered by the G-E General Engineering and Consulting Laboratory, the betatron includes a 160-ton magnet, a 24,000-kva capacitor bank, power and electronic cubicles, and a control console. The magnet, which was engineered in the G-E Pittsfield, Mass. Works, was shipped to Chicago in sections, the largest of which weighed 35 tons.

In principle, the betatron might be compared to an ordinary transformer. Instead of the usual secondary coil, however, a doughnut-shaped vacuum tube is placed within the magnetic field. Sealed to the doughnut is an arm with an electron gun that serves as a source of electrons. These electrons are shot tangentially into the doughnut and are acted upon by the magnetic field, which causes them to travel around the tube. During each revolution the same voltage increase is achieved as though they had flowed through a single turn of wire. After approximately 250,000 revolutions the electrons reach the rated energy level and they are then magnetically guided from the circular path and made to strike a target. When high speed electrons are stopped by a target, x-rays are produced. The wave length or "hardness" of these rays is determined by the energy of the bombarding electrons, which in this case is a hundred times as great as for conventional x-ray machines. At such energies the x-rays emerge from the betatron in a narrow beam and it is this beam which is utilized for experiments.



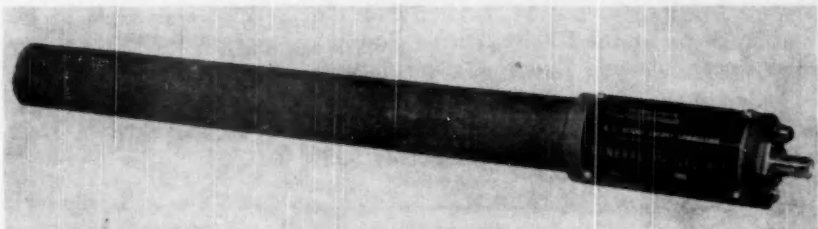
The new 100 Mev Betatron being installed at the University of Chicago

New Boron Lined Neutron Counter Tube

A new proportional counter tube, sensitive to thermal neutrons, has been announced by the Special Products Division of the General Electric Co. The boron lined neutron counter tube will enable measurements of slow neutron intensities for nuclear scientific purposes.

The new counter tube was designed by the General Electric General Engineering and Consulting Laboratory. Two important applications are health physics and pile technology.

The cathode cylinder is made from seamless steel tubing. The internal



G-E Neutron Counter Tube

surfaces of the cylinder are coated with metallic boron enriched in the isotope Boron 10 which has a large effective area for the capture of slow neutrons. The cylinder is filled with a gas mixture to obtain self quenching action. The boron coating represents a thin foil which is immersed in a stream of slow neutrons. The nucleus of the boron 10 isotope on capturing a slow neutron, disintegrates into an alpha particle and a lithium nucleus, with a release of a known amount of energy. This energy is shared by the two particles which fly apart in opposite directions. Because these particles are positively charged, they react with the electrons in the gas that is sealed in the tube. Thus ionization takes place in the tube. The liberated electrons are collected by a thin anode stainless steel wire, that is located longitudinally in the center of the tube, causing a momentary ionization current. This in turn is amplified and recorded.

The counter is so constructed as to have all external high voltage points shielded electrically and physically. Tubes of 8-inch and 12-inch sensitive length are available.

New Chart Gives Information on More Than 1000 Kinds of Atoms

Information on more than a thousand kinds of atoms is given on a new chart being distributed free to scientists in industrial laboratories, colleges and universities by the General Electric Research Laboratory.

Printed in checkerboard fashion on heavy paper 26 by 50 in. each of the 96 chemical elements which were known at the beginning of the year is given a horizontal line, in which a square is devoted to each kind of atom, or "isotope", of that element.

The shading of each square indicates whether it is a stable form that occurs in nature, a radioactive form that occurs naturally, or one artificially radioactive produced in atom-smashing experiments. Its position on the chart shows the composition of its atomic nucleus, with the number of protons and neutrons. Among data given for each isotope are the proportion that it normally constitutes of the natural element; if radioactive, the speed at which it decays and the radiations emitted; whether it appears

as a product of the fission of uranium 235; and an important technical datum known as the "thermal neutron absorption or activation cross section." For radioactive isotopes the speed of decay and the radiations emitted are given.

It is known as the "Chart of the Nuclides." The word "nuclide" is a general term, given to different kinds of atomic nuclei whether of the same or of different elements.

The first edition of the chart (then called "Chart of the Isotopes") was issued in May, 1948. It was prepared in the G-E Research Laboratory by Drs. G. Friedlander and M. L. Perlman. The revision was made by Dr. John R. Stehn of the Knolls Atomic Power Laboratory, which G-E. operates for the Atomic Energy Commission.

Copies of the chart and an accompanying explanatory booklet will be mailed free to interested persons. Requests should be addressed to Dept. 6-221, General Electric Co., Schenectady 5, N. Y.

New Books on Atomics

Phenomena, Atoms and Molecules by Irving Langmuir. First Edition; 6¼ by 9¼ in.; 436 pages; cloth; published by the Philosophical Library, Inc., 15 E. 40th Street, New York 16, N. Y. 1950. Price \$10.00.

Strangely enough, despite Dr. Langmuir's many papers before scientific and engineering societies during the past 30 years, this is his first book. As might be expected, it is a very interesting book and one that everyone who has followed Dr. Langmuir's researches at the General Electric Company's Research Laboratory will want to read. In it he sets down his thoughts, observations and conclusions from his lifetime in the world of science. His approach to sociological and international aspects of modern science, along with a comprehensive discussion of atomic progress and possibilities.

Inventor of the gas-filled tungsten lamp, pioneer in the development of the high vacuum electron tube, the first to isolate atomic hydrogen and demonstrate the importance to chemistry and physics of single layers of atoms and molecules, Dr. Langmuir here offers a work that possesses importance and timeliness.

For many years, Dr. Langmuir has been particularly interested in the action of atomic hydrogen and it is not surprising, therefore, to find three of the 18 chapters in the book devoted entirely to various aspects of atomic hydrogen. Aside from the purely scientific chapters, the first chapter on science, common sense and decency will be of particular interest to everyone, both scientists and laymen alike. We cannot recommend this book too highly.

**Any book described in this department may be purchased from
the Book Department, ATOMICS, Technical Publishing Company,
110 S. Dearborn, Chicago 3, Illinois**

The Atomics Bookshelf

Introduction to Radiochemistry. By Gerhart Friedlander and Joseph W. Kennedy. John Wiley & Sons, Inc. \$5.00

An excellent, up-to-date book describing the nature and applications of radioactivity without assuming previous knowledge of nuclear physics. It begins with a brief discussion of the historical background which is used as an introduction to the early chapters on descriptive information about atomic nuclei, nuclear reactions, and the apparatus used for the acceleration of nuclear projectiles. Later chapters discuss all aspects of nuclear phenomena.

Radioactive Tracer Techniques. By Geo. K. Schweitzer and Ira B. Whitney. D. Van Nostrand Co. \$3.85

A useful manual designed to serve as a guide for laboratory work and instruction in the use of radioactive tracers. It should be of value to all who may have use for radioactive isotopes as tracers in industrial or medical applications.

The Atomic Story. By John W. Campbell. Henry Holt & Co., \$3.00

By all odds the best and most interesting book on atomic energy for the layman. Written by a man who possesses the unique combination of writing ability and technical knowledge, it is first of all a story, not a treatise. At the same time it is accurate. It is the most important story of our time told in simple language by a man who has spent many years in the field of science fiction. He is the Editor of *Astounding Science Fiction*.

The Strange Story of the Quantum. By Banesh Hoffman. Harper & Brothers, \$3.00

Easily the best account of the growth of the ideas underlying our present knowledge of atomic structure, prepared for the reader not especially trained in nuclear physics. It has taken one of the most abstruse and difficult questions—just how matter and energy are put together—and made it readable and understandable as it can be.

The Science and Engineering of Nuclear Power. Two Volumes. Edited by Clark Goodman. Addison Wesley Press, Inc., \$7.50 each

These two volumes contain the essentials of a series of seminars initiated at MIT in October 1946. They provide, by far, the most valuable and usable technical material for the engineer available today. Their objective is to present the fundamentals of chain reacting systems in terms that are understandable to engineers interested in the industrial applications of nuclear energy.

Atomic Energy. By Karl K. Darrow. John Wiley & Sons, Inc., \$2.00

The exciting story of the development of nuclear physics—a story climaxed by the reality of atomic energy and the atomic bomb. Told by an expert who can speak the layman's language.

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needs of key engineers in industry**

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POWER ENGINEERING'S editorial objective—one that differentiates it from all other publications—is to concentrate exclusively on the day-by-day job interests and long range responsibilities of the men who look after the design, construction, management, operation and maintenance of power plants in utility, manufacturing and institutional establishments.

It covers all types of power plants from the large steam and hydroelectric stations to the small plant generating steam or power. POWER ENGINEERING covers not only the production of steam and electricity but also its transmission, distribution and use, as they affect the problems of the power engineer.

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Sample copies of either or both of the above magazines are available on request.

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